XEUS - The X-ray Evolving Universe Spectroscopy Mission

A.N. Parmar[1], T. Peacock[1], M. Bavdaz[1], G. Hasinger[2], M. Arnaud[3], X. Barcons[4], D. Barret[5], A. Blanchard[6], H. Böhringer[7], M. Cappi[8], A. Comastri[9], T. Courvoisier[10], A.C. Fabian[11], R. Griffiths[12], P. Malaguti[8], K.O. Mason[13], T. Ohashi[14], F. Paerels[15], L. Piro[16], J. Schmitt[17], M. van der Klis[18], M. Ward[19]

[1] *Space Science Department of ESA, ESTEC, NL*
[2] *Astrophysikalisches Institut Potsdam, 14482 Potsdam, Germany*
[3] *CEA/DSM/DAPNIA/SAP CEN-Saclay, Gif-sur-Yvette, France*
[4] *IFCA Universidad de Cantabria (CSIC-UC) Santander, Spain*
[5] *CESR-CNRS/UPS, Toulouse, France*
[6] *Observatoire Astronomique de Strasbourg, Strasbourg, France*
[7] *MPE für Extraterrestrische Physik, Garching bei München, Germany*
[8] *Istituto TESRE, CNR, Bologna, Italy*
[9] *Osservatorio Astronomico di Bologna, 40127 Bologna, Italy*
[10] *Observatoire de Geneve, Sauverny, Switzerland*
[11] *Institute of Astronomy, Cambridge, UK*
[12] *Carnegie Mellon University, Pittsburgh, PA, USA*
[13] *Mullard Space Science Laboratory, UCL, Dorking, UK*
[14] *Tokyo Metropolitan University, Hachioji, Tokyo, Japan*
[15] *Space Research Organization Netherlands, Utrecht, NL*
[16] *Istituto di Astrofisica Spaziale (IAS), CNR, 00133 Rome, Italy*
[17] *Universität Hamburg, Hamburger Sternwarte, Hamburg, Germany*
[18] *Astronomical Institute Anton Pannekoek, University of Amsterdam, NL*
[19] *X-ray Astronomy Group, University of Leicester, Leicester, UK*

Abstract. XEUS is under study by ESA as part of the Horizon 2000+ program to utilize the International Space Station (ISS) for astronomical applications. XEUS will be a long-term X-ray observatory with an initial mirror area of 6 m^2 at 1 keV that will be grown to 30 m^2 following a visit to the ISS. The 1 keV spatial resolution is expected to be 2–5$''$ HEW. XEUS will consist of separate detector and mirror spacecraft aligned by active control to provide a focal length of 50 m. A new detector spacecraft, complete with the next generation of instruments, will also be added after visiting the ISS. The limiting sensitivity will then be $\sim 4 \times 10^{-18}$ erg cm^{-2} s^{-1}, around 250 times better than XMM, allowing XEUS to study the properties of the hot baryons and dark matter at high redshift.

1 Introduction

XEUS, the X-ray Evolving Universe Spectroscopy mission, is a potential follow-on mission to XMM and is being studied as part of the Horizon 2000+ program

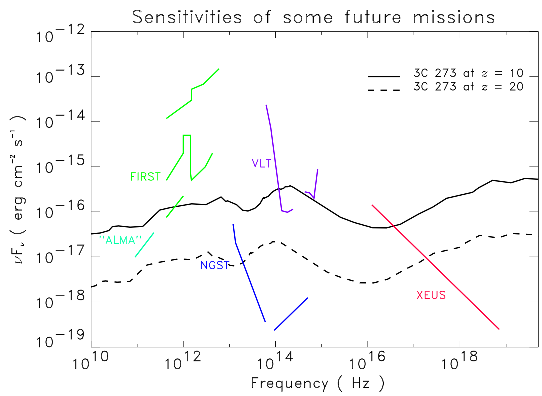

Figure 1: Comparison of the sensitivities of future missions in different wavebands. A horizontal line corresponds to equal power output per decade of frequency. For ALMA an 8 hr integration was assumed, for FIRST a 5σ detection in 1 hr, for NGST a 5σ detection in 10 ks, and for XEUS a 100 ks exposure

within the context of the International Space Station (ISS) utilization. The XEUS mission aims to place a long lived X-ray observatory in space with a sensitivity comparable to the next generation of ground and space based observatories such as ALMA and NGST (Fig. 1). By making full use of the facilities available at the ISS and by ensuring in the design a significant growth and evolution potential, the overall mission lifetime of XEUS could be >25 years.

The key characteristic of XEUS is the large aperture X-ray mirror. This will capitalize on the successful XMM mirror technology and the industrial foundations which have been already laid in Europe for this program. The XEUS mirror aperture of 10 m diameter will be divided into annuli with each annulus subdivided into sectors. The basic mirror unit therefore consists of a set of heavily stacked thin mirror plates. This unit is known as a "mirror petal" and is a complete, free standing, calibrated part of the overall XEUS optics with a spatial resolution of 2–5$''$ HEW and a broad energy range of 0.05–30 keV. Each mirror petal will be individually alignable in orbit. Narrow and Wide field imagers will provide FOVs of $1'$ and $5'$, and energy resolutions of 1–2 eV and 50 eV at 1 keV.

2 Mission Profile

XEUS will consist of separate detector (DSC) and mirror spacecraft (MSC) separated by 50 m and aligned by active control. The large aperture mirror cannot be deployed in a single launch. Instead, the "zero growth" XEUS (MSC1+DSC1)

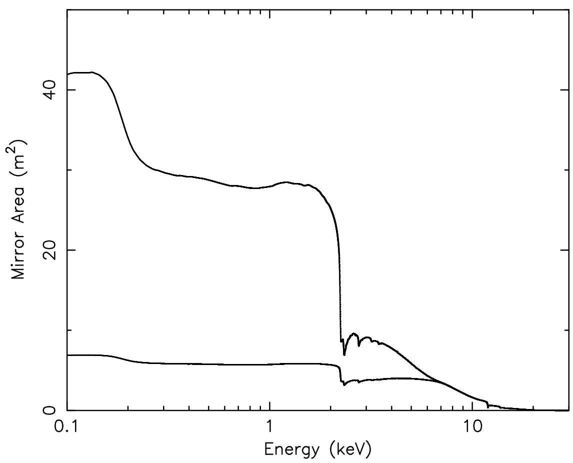

Figure 2: The XEUS mirror area before and after growth at the ISS

will be launched directly into a Fellow Traveler Orbit (FTO) to the ISS using an Ariane V or similar. The FTO is a low Earth orbit with an altitude of ~600 km and an inclination similar to the ISS. The mated pair will then decouple and DSC1 will take up station 50 m from the MSC1 and after check-out the zero growth astrophysics observation program will commence with an aperture of 6 m^2 at 1 keV.

After 4–5 years of observations, the XEUS spacecraft will re-mate and maneuver to the vicinity of the ISS. At the ISS the MSC1 will separate from DSC1 and then dock with the ISS. The DSC1, with its usefulness at an end, will undergo a controlled de-orbit. At the ISS the mirror area is expanded to 30 m^2 at 1 keV (see Fig. 2) and MSC1 becomes MSC2. The extra mirror petals will have already been transported to the ISS using the STS or the European Automated Transfer Vehicle (ATV). Once the mirror growth and checkout is complete, MSC2 will leave the ISS and mate with the recently launched DSC2. Using the DSC2 propulsion system the pair will return to FTO and the fully grown XEUS will start its observing program.

3 Science Goals

XEUS will study the evolution of the hot baryons in the Universe and in particular:

- Detect massive black holes in the earliest AGN and estimate their mass, spin and z through studies of relativistically broadened Fe-K lines and variability.
- Study the formation of the first gravitationally bound, dark matter dominated, systems ie. small groups of galaxies and trace their evolution into

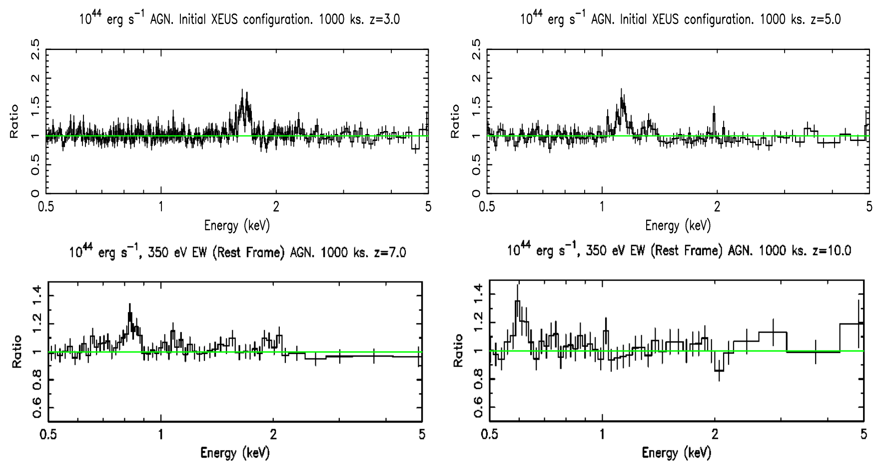

Figure 3: The residuals when the 350 eV EW Fe line normalization is set to zero for an AGN with a (rest-frame) luminosity of 10^{44} erg s^{-1} for z = 3, 5, 7, and 10 for the fully grown XEUS configuration.

today's massive clusters.

- Study the evolution of metal synthesis down to the present epoch, using in particular, observations of the hot intra-cluster gas.
- Characterize the mass, temperature, density of the intergalactic medium, much of which may be in hot filamentary structures, using aborption line spectroscopy. High z luminous quasars and X-ray afterglows of gamma-ray bursts can be used as background sources.

3.1 Spectroscopy of Massive Black holes

Currently, X-ray astronomy can only detect AGN to a z of $\sim$5. XEUS will be able to undertake *detailed* X-ray spectroscopy of much more distant AGN. Fig. 3 illustrates the results of a series of simulations of a "typical" AGN with a 2–10 keV rest-frame luminosity of 10^{44} erg s^{-1} at different red-shifts. An exposure time of 10^6 s was assumed for the fully grown XEUS. Values for H_0 and q_0 of 50 km s^{-1} Mpc^{-1} and 0.5 together with an underlying $E^{-2.0}$ spectrum with a Galactic N_H of 10^{21} atom cm^{-2} and a local (red-shifted) N_H of 5×10^{21} atom cm^{-2} were assumed. A "double-horned" relativistically distorted and Doppler broadened Fe line at 6.4 keV with a rest-frame equivalent width of 350 eV was simulated. The other line parameters were taken to be as for MCG-6-30-15. Fig. 3 shows the residuals when the source is red-shifted to z = 3, 5, 7, and 10, demonstrating that such a line can be clearly detected and its properties measured even at z = 10.

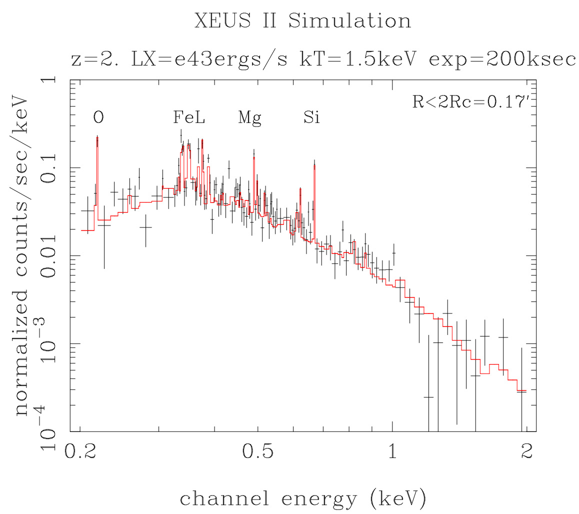

Figure 4: Simulated XEUS spectrum of a $z = 2$ galaxy group.

3.2 Spectroscopy of Distant Galaxy Groups

To illustrate the potential of XEUS to study the formation of large scale structure Fig. 4 shows a simulation of a distant ($z = 2$) galaxy group. In standard cosmological models these groups are the first emerging massive objects, with masses of $\sim 10^{13} M_{\odot}$. The epoch of their first formation depends critically on the adopted cosmology, and is likely to be $z \sim 2$–5. Therefore the study of groups will provide a deep probe of the early Universe. These systems and their dark matter aloes are the smallest units by which to study the hot thermal intergalactic gas trapped in deep gravitational wells. Emission lines of O, Fe, Mg, and Si are clearly evident. The temperature can be determined to better than $\pm 3\%$ and the Fe and O abundances to better than 10% and 20%, respectively.

3.3 Resonant Absorption Line Studies

XEUS will be the first X-ray observatory capable of detecting resonance absorption lines for a wide range of objects. This results from the unique combination of large effective area and high spectral and spatial resolutions. The use of resonance absorption lines can be applied to several problems, as it is in optical/UV astronomy. Resonance absorption lines are generally detectable at much lower column densities than absorption edges (which do not require high resolution spectroscopy), and therefore can trace gas which is too tenuous to be seen by other means.

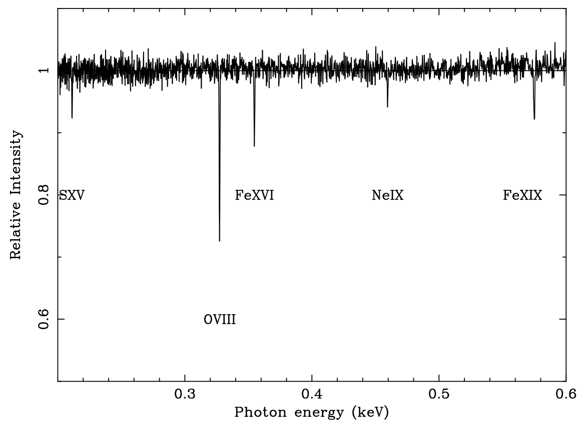

Figure 5: Absorption line spectrum towards a $10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ AGN (0.5–2 keV) observed for 100 ks with XEUS2. The line of sight is assumed to cross a small group (L=$10^{42}\mathrm{erg\,s^{-1}}$) at $z = 1$ with a core of radius 50 kpc. For a $10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ background source, the O VIII line is still clearly detected.

Intervening hot/warm gas clouds along the line of sight towards distant background sources will produce resonance absorption lines. The main issues that can be addressed with these studies include the use of absorber number counts and their redshift dependence to test models of large-scale structure formation, the determination of the temperature distribution of baryons in the Universe, the determination of metallicities of the absorbers, and in particular the [O/Fe] ratio to infer the relative rates of type I and II Supernovae, the determination of the redshift evolution of parameters such as number counts, gas kTs, and metallicities, and when the emitting gas is also seen in absorption, the use both emission and absorption to infer distances, and therefore measure key cosmological parameters.

3.4 Studying Dust Enshrouded AGN and Starburst Galaxies

In order to test the sensitivity of XEUS to discriminate between AGN and starburst emission, spectra of a composite starburst galaxy plus a heavily absorbed AGN have been simulated. The starburst emission was parameterized by a thermal gas at kT = 3 keV with 0.3 solar metallicity. Above a few keV the absorbed AGN is expected to show up with a strong (EW = 1 keV) Fe-K line due to transmission through the $N_H=10^{24}$ cm^{-2} absorbing material. Such a model is similar to that of the nearby galaxies NGC 6240, NGC 4945, and Mkn 3. Fig. 6 demonstrates that XEUS1 will allow a detailed study of such sources around $z = 1$, but that XEUS2 is required to perform spectroscopy at $z \gg 1$. Such X-ray spectra

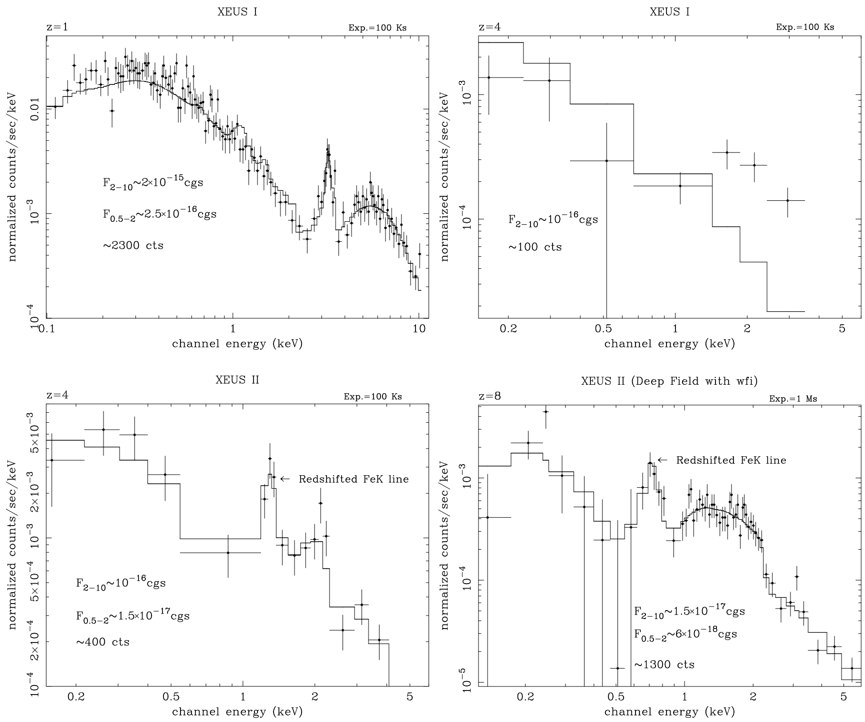

Figure 6: Upper panels: simulated XEUS1 spectra at $z = 1$ (Left) and $z = 4$ (Right). These illustrate the limits of the XEUS prior to growth at the ISS. The lower panels show simulated XEUS2 spectra (after mirror growth) at $z = 4$ (Left) and $z = 8$ (Right).

are the only way to obtain *direct* proof of the existence of dust-enshrouded AGNs at high redshift. If detected, they would allow the starburst versus AGN contribution to be directly disentangled. If undetected, they would give strong limits on the AGN contribution. This would have important consequences on the star formation and ionization histories of the Universe.

3.5 Stellar Spectroscopy

The large effective area of the XEUS configuration provides unique opportunities for stellar X-ray astronomy. The high sensitivity means that solar-like X-ray emission can be detected out to distances of a few kpc. As a consequence large samples of truly solar-like stars become amenable for study. For example, at the

distance of M 67, an old open cluster with an age similar to that of the Sun, a limiting X-ray luminosity of 10^{26} erg s^{-1} can be reached, implying that solar minimum X-ray emission levels can be detected. This is particularly relevant for a study of activity cycles in other solar-like stars, since in the Sun the solar cycle is most easily detectable in the X-ray domain. In addition, the XEUS sensitivity is so large that in nearby open clusters such as Hyades and Pleiades virtually all cluster stars will be detectable as X-ray sources, and the X-ray brightest cool stars can even be detected in nearby galaxies such as the LMC and M 31.

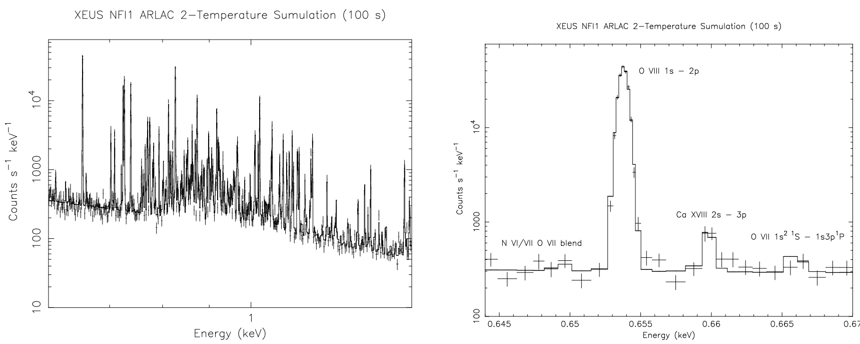

Figure 7: (left) Parts of a simulated NFI1 spectrum of AR Lac with the XEUS1 configuration showing details of the Fe-L region (left). An exposure time of 100 s was used. A similar quality spectrum is expected in only 20 s with XEUS2. (right) The spectral region near oxygen Ly-α with line identifications.

X-ray images of the Sun have revealed that hot plasma trapped in closed magnetic loops provides almost all of the solar X-ray emission. While such X-ray emission is usually "quiet", sometimes restructuring of such magnetic loops gives rise to intense outbursts of radiation in the form of flares. On other stars flare much more intense than those on the Sun are observed. Time resolved high resolution spectroscopy is required to understand and analyze the physics of such giant stellar flares. The potential of XEUS to perform such studies is illustrated by simulations of the nearby RS CVn system AR Lac (G2 IV + K0 IV). The 100 s simulations shown in Fig. 7 show parts of a rich line-dominated spectrum. The large area of XEUS means that a sufficient number of counts are obtained so that the temperature, density, chemical abundance and velocity distribution of the emitting plasma can be measured on very short timescales. This will allow the study of the evolution of these basic physical parameters during typical stellar flares with an accuracy only previously achievable with solar flares.

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